ARL-CR-0814 ● MAY 2017

US Army Research Laboratory

Robotics Collaborative Technology Alliance (RCTA): Technical Exchange Meeting (TEM) 2015

by Julian Abich IV, Daniel J Barber, Jonathan Clark, and Emmanuel Collins

NOTICES

Disclaimers

ARL-CR-0814 ● MAY 2017

US Army Research Laboratory

Robotics Collaborative Technology Alliance (RCTA): Technical Exchange Meeting (TEM) 2015

by Julian Abich IV and Daniel J Barber
University of Central Florida, Institute for Simulation and Training, Orlando, FL

Jonathan Clark and Emmanuel Collins
Florida State University, Aero-Propulsion, Mechatronics, and Energy, Tallahassee, FL

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
May 2017	Contractor Report	1 January 2015–31 December 2016

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
Robotics Collaborative Technology Alliance (RCTA): Technical Exchange Meeting (TEM) 2015	W911NF-10-2-0016
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Julian Abich IV,* Daniel J Barber,* Jonathan Clark,† and Emmanuel Collins†	W911NF-10-2-0016
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
US Army Research Laboratory ATTN: RDRL-HRF-D Aberdeen Proving Ground, MD 21005-5425	ARL-CR-0814
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

* Institute for Simulation and Training, University of Central Florida
† Aero-Propulsion, Mechatronics, and Energy, Florida State University

14. ABSTRACT

This report describes the outcomes of a 2015 Technical Exchange Meeting (TEM) dedicated to identifying the gaps and prioritizing critical research areas in the human–robot interaction (HRI) field, focusing on unique mobility robots (UMRs) with special manipulation capabilities to progress peer-to-peer, tactical human–robot teaming. The TEM was held to develop a unified vision for HRI research to enable teaming among Soldiers and UMRs and to identify points of intersection in the Robotics Collaborative Technology Alliance (RCTA) to facilitate HRI research. Accomplishing this goal required input from all RCTA technical areas including Dexterous Manipulation and Unique Mobility, Intelligence, and Perception. The TEM achieved the following: a joint understanding of the state of the art of UMRs, identification of technical areas in which HRI can assist UMRs and support prototype delivery, and prioritization of an action plan for future HRI in UMR research.

15. SUBJECT TERMS

human–robot interaction, human–robot teams, unique mobility robots, dexterous manipulation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Kristin Schaefer-Lay
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER (Include area code)**
Unclassified	Unclassified	Unclassified	UU	40	407-562-7779

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

List of Tables

Acknowledgments

We are indebted to the workshop attendees who participated readily and steadily throughout this event, providing insightful comments, discussion, and active attention. This research was sponsored by the US Army Research Laboratory (ARL) and was accomplished under Cooperative Agreement no. W911NF-10-2-0016. The views and conclusions contained in this report are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of ARL, the US Government, or any of the participant attendees. All statements of fact or opinion presented in this report are those of the meeting's participants and do not reflect positions or views of their employers or any organizations with which they are affiliated. The US Government is authorized to reproduce and distribute reprints for government purposes notwithstanding any copyright notation hereon.

1. Introduction

This report describes the outcomes of a meeting that was dedicated to identifying gaps and prioritizing critical research areas in the field of human–robot interaction (HRI)—focusing on robots with unique mobility and manipulation capabilities to progress peer-to-peer, tactical human–robot teaming. The US Army Research Laboratory (ARL)-sponsored Robotics Collaborative Technology Alliance (RCTA): Technical Exchange Meeting (TEM) 2015 was organized by the University of Central Florida (UCF) and Florida State University (FSU) and held on 8–9 December 2015 at the UCF Institute for Simulation and Training in Research Park, Orlando, Florida. This interdisciplinary effort by multiple universities, industry organizations, and personnel from various government branches examined the current and future state of HRI with unique mobility robot (UMR) teammates in dismounted military operations. The TEM's goal was a unified vision for HRI research to enable teaming between Soldiers and UMRs and to identify points of intersection within the RCTA to facilitate HRI research. Accomplishing the goal required input from all RCTA technical areas: HRI, Dexterous Manipulation and Unique Mobility (DMUM), Intelligence, and Perception. The 2-day TEM comprised lectures, breakout sessions, and group discussions.

The overall objectives for the meeting are listed as follows:

1) Acquire an improved understanding of the state of the art and planned accomplishments within the RCTA over the next 4 years in support of UMRs
2) Identify technical areas in which HRI can deliver research results and prototypes for UMRs
3) Identify technical areas in which HRI can assist in UMRs
4) Formalize discussions into a technical report and special edition of a "Frontiers in" journal[*] to guide future research deliverables

1.1 Meeting Orientation

The current state of HRI research in the context of UMR interaction was the motivation to have this meeting. Within the RCTA's contextual domain, a dismounted military setting, most HRI research over the past 5 years has focused on interaction with unmanned ground vehicles (UGVs) or tracked-based robots

[*] The open-access, academic publisher's website is http://home.frontiersin.org.

through teleoperation or mixed initiative control. Despite the vast progress in this line of research, robots with unique mobility and dexterous manipulations are gaining momentum in the field of robotics and show great promise in dismounted Soldier–robot team applications. UMRs are platforms that move beyond the use of conventional locomotion (i.e., wheels or tracks) and are capable of adapting to a multitude of environmental terrains that would otherwise limit conventional locomotion platforms (Hong 2006). Dexterous manipulation refers to the capability of a robotic platform to coordinate an interaction with objects in the environment through the use of arms, hands, fingers, grippers, and other manipulators (Okamura and Smaby 2000). The RCTA's goal is to develop highly autonomous systems with a set of intelligence and perception capabilities able to manipulate complex environments, ultimately enabling efficient and effective mixed-initiative, dismounted Soldier–robot teaming; thus, 2 foundational issues must be addressed regarding HRI with UMRs:

1) From the HRI research conducted with wheeled or tracked UGVs, what information and results regarding interaction with conventional platforms will or will not transfer to interaction with UMRs?

2) What are the HRI challenges that have not been addressed with UMR interaction or could not be addressed by investigating HRI with wheeled or tracked vehicles?

The inherent limitations of the conventional types of platforms for dismounted military operations are the impetus to explore other robotic systems equipped with higher degrees of freedom and unique functionality. Therefore, in order to grasp the current state of the art of UMR and share a common vision of foreseeable research and applications of the future, experts from academia, government, and industry discussed and identified the gaps in HRI for UMR research that need to be filled to meet the RCTA program's goal.

1.1.1 Use Case for Discussion

To further ground RCTA-TEM discussions with an applied context, Cordon and Search (C& S) operations were presented as a use case. The C&S operation is one of the most frequently used tactics of dismounted Soldier teams in complex urban environments because they are effective for area reconnaissance, enemy isolation and capture, and weapons and material seizures (Sutherland et al. 2010). The multifaceted organization required to perform C&S operations provide opportunities to use robot teammates as key elements to both increase the effectiveness of these operations and to reduce Soldier exposure to danger.

A C&S team usually comprises 4 elements: 1) command, 2) security, 3) search/assault, and 4) reserve. Besides the command element, robot teammates can potentially serve in the other 3 elements because these roles are the most hazardous for Soldiers and operations could benefit greatly from UMR capabilities and functionality. The security element comprises the inner and outer cordon. The outer cordon secures the cordoned area by not allowing any intrusions into the search area and usually requires covering/monitoring a large area. The inner cordon observes the search area and ensures potential threats neither enter nor leave the specific area. The search/assault element performs the actual search of the area of interest, whether it is a building, portion of a building, or other setting. Additionally, the reserve element supports the other C&S elements when needed; therefore, it must be able to adapt to unanticipated events and perform any task needed to maintain control of the situation. Figure 1 depicts a notional C&S operation involving 3 robots.

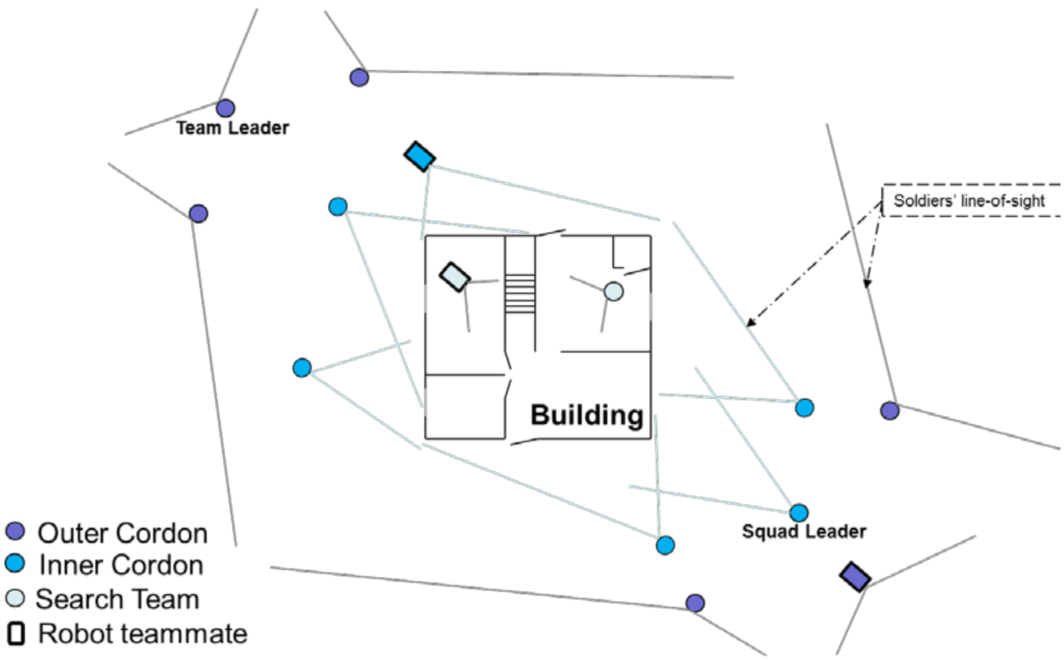

Fig. 1 Example of a C&S operation with location of each cordon element: reserve element (if available) would take on 1 of the 3 roles shown, depending on the situation; symbols for each element may represent multiple team members

1.1.2 "Cordon and Kick" vs. "Cordon and Knock or Ask"

C&S operations fall under 2 categories: "Cordon and Kick" or "Cordon and Knock or Ask." The first is a time-sensitive, brute-force approach requiring the search team to knock down doors and search as quickly as possible. The element of surprise is key to reduce or prevent any preparations executed by the opposition. Immediate and constant communication between team members is vital. The latter

approach is more cordial and relaxed; the search team asks residents or owners for permission to search the premises. This is done when military-intelligence reports indicate no threats are suspected in the vicinity and to avoid hostile situations with friendly civilians.

1.2 Presentations

The TEM was organized based on the RCTA's core technical areas: 1) HRI, 2) DMUM, 3) Perception, and 4) Intelligence. The purpose and objectives for the meeting and a general overview of HRI were presented first to describe the current state of HRI research within the RCTA, to illustrate the role HRI plays within all of the core technical areas, and to emphasize the need for collaborations with all core technical areas in order to reach the RCTA's goal of effective dismounted, multiunit Soldier–robot teaming.

The presentations were as follows:

HRI

- RCTA 2015 Joint HRI–DMUM TEM: Purpose and Objectives—Daniel Barber, UCF
- RCTA 2015 Joint HRI–DMUM TEM: Overview—Florian Jentsch, UCF

Integrated Research Assessment (IRA)

- RCTA 2015-20 IRA Framework Rhythm—Chip DiBerardino, General Dynamics Land Systems (GDLS)

DMUM

- DMUM overview and relations to HRI—Jonathan Clark and Emmanuel Collins, FSU

Perception

- Perception—Martial Herbert, Carnegie Mellon University (CMU)

Intelligence

- RCTA: Program and Intelligence Architecture Overview—Robert Dean, GDLS
- Autonomous Behaviors: ARL Autonomous Systems Enterprise—Stuart Young, ARL

- Soldier Intent for Fully Responsive Autonomous Systems—Douglas Summers-Stay, ARL

1.3 Meeting Breakout and Discussion Sessions

Following each presentation, 3 groups were formed to answer questions about the presentation. The groups were predetermined to ensure participants were from various backgrounds and organizations to support an interdisciplinary approach to the HRI for UMR topics. The groups then reunited and discussed their responses to the same questions. The group responses were compiled and organized into themes. Discussion groups generated additional questions associated with gaps and intersection points within HRI for UMR research.

Prior to the TEM, a list of potential questions was generated for each core technical area based on the proposed tasks and subtasks of the 2015–2017 RCTA Bi-Annual Program Plan. Following initial question generation, key leads and presenters from each technical area were contacted to review the list and modify or generate more discussion items. To facilitate the discussion and inclusion from personnel in each technical core area, each group session was dedicated to one core area. Within each group, designated HRI personnel took the role of group lead to ensure each question was addressed, keep discussion within the allotted time frame, and gather detailed notes from the responses. The notes from the breakout and full group discussions were compiled, analyzed, and synthesized into areas that shared common themes. From that came the following sections to be discussed in more detail: current state of UMR and research questions that should be addressed. (Appendix A of this report is the TEM's agenda, Appendix B is discussion questions, and Appendix C lists workshop attendees.)

2. Current State of Unique Mobility Robots

Among the TEM attendees were many experts in robotics who provided a great deal of information on the current state of UMR capabilities and functionality. During each group discussion, experts were queried about the advantages UMR robots have over humans and the limitations that still exist regarding each of the core theme areas of the RCTA.

2.1 Advantages of Robots

Robots possess many advantages over humans and are currently used in various areas such as the military, hospitals, industrial/manufacturing, agriculture, security, and inhospitable environments. Robots have a finer degree of manipulation for

precision and dexterity (Soffar 2015), making them suitable for tasks that require fine motor movements such as laparoscopic surgery (Chiu et al. 2015). Some, such as the FANUC (RobotWorx 2016), are capable of continuous 360° rotation of the wrists—whereas a human has to return the wrist to the same position after about a single 180° rotation. Some robots equal in size to humans are physically stronger and could reach or traverse difficult terrain beyond human limitations, such as the RoboSimian (Hebert et al. 2015). Additionally, some platforms can fit into small and tight-volume locations that are impossible for humans to penetrate, such as the modular snake robot that can wind itself through pipes or up poles (Wright et al. 2007). Robots are advantageous in industry because of their ability to continuously perform monotonous tasks without fatigue (Soffar 2015), which suggests surveillance requiring long hours of vigilance would be a potential use for robots. Robots can even act as surrogates for humans when it is necessary to handle volatile substances or enter hazardous environments (Markoff 2012).

Robotic perception may exceed humans' in many respects such as in detection of electromagnetic radiation waves not in the visible spectrum through the use of infrared transceivers (Arvin et al. 2009), ultrasonic sensors (Kim and Kim 2013), and photo resistors (Russell et al. 2015). Some are capable of thermal and X-ray imaging to see through walls and detect heat signatures from humans, animals, or insects. The Termibot is equipped with thermal imaging, which allows it to noninvasively detect the location of termites (Blain 2007). Extensive data logging and immediate assimilation into long-term storage can help augment human perception and understanding of the operation to better support detailed and more thorough after-action reviews.

From an intelligence perspective, robots have some level of self-awareness and a decent understanding of their physical footprint, but the ability to understand their place in the environment is limited to the sensor capabilities; yet, they have the ability to understand intervisibility (i.e., state of being mutually visible) (Afeni and Cawood 2013). The most advanced intellectual capability is rapid, precise, and extensive computational processing. To some extent, robots are able to learn from a comparison of past experience, user input, and current memory store. Pointeau et al. (2014) have successfully demonstrated a humanoid robot capable of extracting information through social interactions and developing representations of common experiences.

The past 2 decades have seen tremendous improvements in robot functionality and capabilities (Table 1), but progress takes time due to the intricacies of development and testing. Therefore, HRI research must identify the optimal ways of leveraging these robot improvements for human–robot teaming, yet remain cognizant of the

technological limitations, to appropriately determine the implementation of human assistance.

Table 1 Current and future platforms and capabilities the RCTA will use to investigate Soldier–robot team performance

Husky (wheeled)	RoMan (manipulators)	Minitaur (legged)	Snake
Bump Navigate Search Observe Go to (x) Chain actions Follow[a] Lead[a] Recon[a] Rally[a]	Push Pick up with 1 hand, with 2 hands Drag Rotate Pull Open door[a]	Walk Run (trot) Bound Leap over[a] Climb stairs, walls[a] Rear up (perch on)	Corkscrew (pipe mode)[a] Sidewind[a] Climb pole[a] Orient—look/track[a] Potential to swim or hide (in sand, rocks)

[a] Capabilities unique for each robot platform that are currently implemented or being worked on within the program

2.2 Limitations of Robots

Although robots have many advantages over humans, they do not exist without limitations. These limitations provide intersections for HRI intervention. For instance, robot capabilities are very specific to tasks; therefore, no robot has a general suite of capabilities similar to humans, which makes it difficult for nonhomogeneous UMRs to coordinate and assign tasks to one another. For these reasons, humans may be better suited at managing varying robot assets, especially since robots do not possess the same level of complex decision making. Another common limitation is their insensitivity in handling fragile objects as they may be prone to exerting forces beyond an object's sustainable threshold—or not exert enough force to properly grasp an object with low-friction surfaces. Fingertip sensors are capable of classifying tactile stimulation (Shill et al. 2015), but human receptors are more keen at distinguishing an extensively larger array of surfaces. This suggests that until robot sensing capabilities reach human standards, humans can aid robots in determining the course of action with various surfaces and textures. Also, robots tend to move much slower than humans due to either computational time for planning or limitations in actuator speeds, and the ones capable of moving at faster speeds do so at high energy costs (Seok et al. 2013). HRI can support decision making when it comes to identifying cost-efficient path planning. Additionally, although robots may possess super-human strength, the cost of production/materials and their physical weight tend to rise with increasing physical strength; however, several smaller robots may be capable of the strength of a single large platform. Again, this may require the assistance of a human to

coordinate or command a team of robots in this type of approach. Further, robots need detailed instructions because of their limited learning capacity; therefore, humans may need to teach various task repertoires so robots will learn how humans complete a task.

Regarding robotic perception, there is a data problem with training different classifiers to detect various surface types and environmental terrains. From a classifier perspective, robots are not well suited for classifying many of the things that humans label in the environment as important, illustrating the need for humans to teach surface and terrain classification. Robots cannot "see" very far due to limitations in sensor ranges and, therefore, cannot make good inferences about terrain far away; humans, however, can coordinate information from various sources (e.g., GPS, satellite imagery, binoculars) and transmit that information to a robot. Robots have difficulty perceiving distinct objects in an extensive range of lighting conditions or visual complexity; shiny objects are a challenge for robots to capture and process visually, yet humans perform these tasks almost effortlessly—again, allowing robots to leverage the sensing capabilities of a human in order to develop cohesive, interdependent human–robot teaming.

In terms of intelligence, there is an abundance of prior knowledge available to Soldiers that is not currently represented in the robot. A major opportunity for HRI is when a robot needs to resolve disambiguation. These situations provide opportunities in which HRI can support robot learning due to the robot's limited learning capacity (as stated previously.

With identification of the advantages and limitations of current robot platforms, research questions are revealed in which humans must assist robots to accomplish tasks that will benefit them both. However, for the human to assist a robot, the robot must in turn support the human in understanding when and how it needs assistance.

3. Research Questions for Future Investigation

A detailed analysis of the resultant notes from the TEM discussions first included categorization of the content in each core technical area. Much of the discussion generated additional questions that were formalized into research topics. The content in each core area was further analyzed for any crossover and synthesized into common themes. The following section describes the gaps identified in HRI for UMR research.

3.1 Communication

What kinds of UMR commands should be investigated?

- What is the appropriate method to communicate the commands (e.g., gesture, speech)?
- Is there an appropriate human-to-human analog of the commands that can be leveraged?
  - For example, there is no direct training or dialogue to tell a Soldier to open a door; in the same regard, there is no foundational language for commanding a robot to climb a wall.
- Are there population-specific differences (e.g., novice vs. Soldier)?
- Are the commands context specific?

Different squads have their own vocabulary built around squad member interactions and experiences.

- Which robot behaviors should be included in a corpus of videos or animations exhibiting how a robot performs, as the result of a specific command, in order to calibrate Soldier expectation of a robot's behavior?
  - Should Soldiers be queried about which commands may have elicited an exhibited behavior and then designate those commands for each of the behaviors?
- Regarding ambiguous situations or cases where a robot might need help, how does a robot convey that it cannot complete a task?
  - What are the dialogue-intersection points between a Soldier and a robot associated with these types of interactions?
  - How do we evaluate the dialogue as effective for issuing and requesting assistance?

How does a Soldier interpret robot intent?

- In what ways can a robot express intent?
- Should a repertoire of intent types be developed?
  - What would these intent types look or sound like when a robot conveys them?

- How do Soldiers infer or ensure the robot’s concept of the world is changing as theirs is?
    - What level of language or communication should be used by a robot to acknowledge change in the environment?

How does a robot interpret a Soldier’s intent?

- Should an intent engine with the ability to tie the commands Soldiers are giving the robot to what is known about the environment be developed?
    - Should physiological sensors, such as gaze detection, be utilized to indicate where the Soldier is looking to determine intent?
        - ✓ Can this information be combined with the knowledge the robot has of the world and try to move from a direct interpretation of what the Soldier said to one with less ambiguity?
            - Can natural language understanding be used to resolve spatial uncertainty?
- Can online learning be incorporated to support the robot’s interpretation of Soldier intent?
    - Should the robot learn from user preference to determine the action it should take?

Can language conveyed from a human provide a robot with enough details to complete a task with minimal human interaction?

- How much information is considered enough?
    - What are the challenges for concise information presentation?
    - How close should grammar sets and vocabulary be defined to match what the Soldiers are going to use to avoid training a specific language?
    - Should general capabilities that may work in many cases first be investigated; then, focus on the edge cases?

3.2 Classification

How should a Soldier help a robot identify and label unknown objects in complex 3-D environments?

- How should a Soldier convey this information to the robot?
- How should the robot display ambiguity when it cannot identify or label an object?
  - Should it be conveyed auditorily, visually, haptically, or in a combination of these?

What types of things should robots prioritize in terms of perception and classification?

- What are the superclasses of things from which other classes are derived?
  - For example, a robot must be able to recognize what it can drive on (potentially, many things). Should there be a superclass for drivable terrain?
- At what point during an interaction must a Soldier convey lower-level class of information when a robot is unable to execute a task based on higher-level superclass of information?

Which parameters for complex 3-D environments should a Soldier have available when issuing commands to a robot?

- What level of language processing is necessary: commands, controlled natural language processing, or open-ended natural language processing?
- What modalities, language, or vocabulary (i.e., speech, gestures, and tactile sequences) will be needed to support these parameters?
- Will different types of vocabulary or language sets be necessary to initiate a task (e.g., "Go to the back of the building.") and transition specific portions of that task (e.g., "Open the gate and move to the left.")?
- Is there enough a priori information about the environment in the robot's dataset to be leveraged by the robot or Soldier during interactions?

- How should baselines or markings be established within new 3-D environments (e.g., describing a building's 1st, 2nd, or 3rd floor)?

How does a robot classify what information is important?

- Should a Soldier determine what a robot should consider as important?
- During training, will Soldiers learn what kind of information the robot will need?
- When it comes to prioritizing tasks, who decides—robot or Soldier—what is the most important?
    - Are there moments when a robot can decide without a human, or should a human always be involved in the final decision?
        - ✓ How does this affect the Soldier's workload?

3.3 Motion

For gait and locomotion does it matter if a robot has mechanical or biological motion?

- Is there an assumption that biological motion is necessary for robots to exhibit effective Soldier–robot teaming?
    - Perhaps a taxonomy is needed concerning the state of the art for motions and mobility.
    - Should animal mobility be reflected in robots that resemble its animal counterpart?
        - ✓ Example: Should the Rhex robot dog have a tail to wag and ears that perk up when it hears a command conveyed from a Soldier?
- Does the gait and locomotion of a robot impact the Soldier's expectation of the robot's performance?
    - Should Soldiers be queried about how they expect a robot to behave and then instill that behavior sequence in a robot?
    - How important is it for effective Soldier–robot teaming that the movement matches the mental model as expected?
    - Does the type of mobility elicit misconceptions of a robot's functionality and capabilities?
        - ✓ How does the Soldier interpret the behavior as a function of the movement?

- To what extent does this influence Soldier trust in the robot?
- Are there parameters associated between the gaits that will need specific commands?

When moving or navigating through complex terrain, how should a Soldier guide or lead a robot?

- When and how often is it appropriate for a robot to ask a Soldier for assistance?
    - How should the assistance request be displayed?
        - ✓ Should it be displayed auditorily, visually, haptically, or in a combination of these?

When a robot manipulates objects it may need for the Soldier to indicate how much force is required to handle an object, or at least label the object to help classify it based on the robot's dataset.

- To what extent does the Soldier need to explain to the robot how it should handle an object?
    - Will providing a robot with labels of objects sufficiently communicate the properties of each object?

Predictability, legibility, and transparency are 3 distinct properties in regard to motion.

The display of the robot's intentions and actions can influence Soldier–robot teaming (Fig. 2).

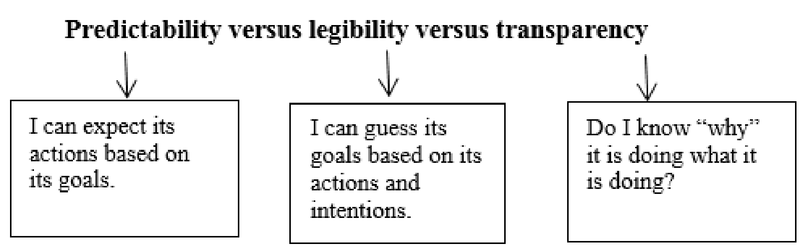

Fig. 2 Three distinct properties of robot motion: predictability, legibility, and transparency

- Are all 3 properties equally important for effective Soldier–robot teaming?
- Do different tasks require different levels of these properties?

3.4 Tasking

What are the types of tasks, actions, and operations Soldiers currently do that might be better suited for a robot in terms of economy, efficiency, and safety?

- What tasks, action, and operations can a robot accomplish that currently are performed by a human?
- What tasks can robots perform that a human cannot perform as efficiently or safely?
- Would it be more plausible to have a continuum of control for some tasks in which the robot initiates an action or behavior and then, if necessary and more beneficial, transitions to the Soldier for completion?

3.5 Teaming

What is the foundation to be built for effective, collaborative training between humans and robots?

- Regarding the “generation gap” between contemporary Soldiers and the future Soldiers who will be more likely to interact with these new robots, what are the differences in their perspectives and views of nonhuman robotic teammates?
- How do we foster acceptance of robot teammates across all generations of Soldiers?

3.6 Summary

Overall, robots are currently limited in their physical mobility and fine-grained manipulation, perception, and intelligence, while the aspect of computational speed is the most advanced functionality. Robot strength is progressing, but there is still a need to work out the supporting physics. In terms of HRI, it is recommended Soldiers train with robots to familiarize themselves with their mobility, motion, and functional abilities. Ideally, through this type of interaction, trust will be fostered (as it is among human teammates). Additionally, transparency of the robot’s intentions, actions, and goals is an important component for building trust among Soldier teammates and should be examined further to enable effective teaming with UMR platforms (Lakhmani et al. 2016).

3.7 Prioritized Questions

The overarching goal of the RCTA is to progress the state of autonomous systems to enable effective, dismounted Soldier–robot teaming. To that end, the objective of this report is to identify and prioritize research areas to be established that will adequately and strategically address the most pertinent gaps regarding HRI with UMR and lay foundations for follow-on research and application. This approach will create a structured and focused vision for HRI research with UMR platforms. With the limited research that exists outside conventional platforms, fundamental knowledge and understanding of various factors contributing to effective HRI with UMR must come first. The following research questions must be answered.

How does a Soldier interpret UMR intent?

- Interpreting intent is vital to the Soldier. Soldiers need to be able to receive information in natural ways to avoid overburdening themselves with the need to learn and remember how to interact with nonhomogeneous UMRs. The robot must indicate to the Soldier that it is receiving a command that it understood the command, is going to perform the command, or needs assistance. Although there has been research in understanding UMR intent within social context, very limited investigation has focused on dismounted military applications. Filling this research gap will allow HRI researchers to evaluate the methods through which Soldiers should expect a robot to express intent. Establishing how this intent should be conveyed will provide robotic hardware and software engineers with guidance for how they should enable robots to perceive and convey intent.

For gait and locomotion does it matter if a robot has mechanical or biological motion in relation to the Soldier's trust, situation awareness, mental models, and ultimately, team performance?

- Intent will help determine the way UMR behaviors are expressed to Soldiers; therefore, the appropriate next step is to determine how those behaviors should be exhibited to support effective teaming. This gap allows HRI researchers to evaluate Soldier interpretation of robot behavior depending on whether it exhibits motion matching their mental models (based on the robot's physical design) or if motion matters less than functionality and capability. This interpretation can affect the expectations Soldiers have for the capabilities of UMRs, which in turn will affect the decisions Soldiers make when tasking UMRs in the field. These findings will provide recommendations to

robotic hardware and software engineers for how robot motion should be exhibited and also identify functional requirements for robot motion.

Do the ways Soldiers communicate with conventional robotic platforms, and vice versa, effectively transfer to interaction with UMRs?

- It is not clear whether the same forms of interaction or information display for wheeled or tracked platforms are the same to support teaming. HRI researchers can evaluate and establish the command vocabulary and gestures Soldiers would use for specific UMR tasks or actions by developing a corpus of video or animation datasets. These videos should reflect the type of behavior Soldiers expect UMRs to perform and how UMRs express their status regarding understanding and execution of commands. Further, the effects of delivery methods through which this information is conveyed and received (e.g., hand-held tablets, heads-up displays) on team performance can also be evaluated for the most appropriate modality and technology for interaction. This again will provide robotic hardware and software engineers with recommendations for how robots should receive and respond to commands.

By addressing these 3 main research gaps, a more thorough understanding of the effects of the UMR's cueing, motion, and information transfer on the Soldier's trust, expectations, situation awareness, mental models, and—most importantly—team performance will help shape future interactions with UMR platforms.

4. Conclusions

In summary, the TEM resulted in identification of the gaps and prioritized critical research areas in the field of human–robot interaction (HRI), specifically involving robots with unique mobility and manipulation capabilities, to progress peer-to-peer tactical human–robot teaming. The culmination of discussion among the TEM attendees resulted in the identification of 3 primary research areas: 1) conveyance of robot intent, 2) impact of robot locomotion on Soldier perception of the robot, and 3) transference of communication interaction to heterogeneous robot platforms. Within these areas are a host of other research questions, but the emphasis of this meeting was to integrate the perspectives of all performers within the program to establish intersections for HRI specifically for UMR research. This interdisciplinary effort among academia, government, and industry exemplified the success of a joint approach to envision the future of UMR research within the focus of the RCTA program goal.

5. References

Afeni T, Cawood F. Slope monitoring using total station: what are the challenges and how should these be mitigated? S Afr J Geomat. 2013;2(1):41–53.

Arvin F, Samsudin K, Ramli A. A short-range infrared communication for swarm mobile robots. International Conference on Signal Processing Systems; 2009; Singapore. Institute of Electrical and Electronics Engineers; p. 454–458.

Blain L. Remote-controlled robot uses thermal imaging to detect and eradicate termites. 2007 May 7. [accessed 2016 July 6]. www.gizmag.com: http://www.gizmag.com/go/7208/.

Chiu LH, Chen CH, Tu PC, Chang CW, Yen YK, Liu WM. Comparison of robotic surgery and laparoscopy to perform total hysterectomy with pelvic adhesions or large uterus. J Min Acc Surg. 2015;11(1):87–93.

Hebert P, Bajracharya M, Ma J, Hudson N, Aydemir A, Reid J, Burdick J. Mobile manipulation and mobility as manipulation-design and algorithms of RoboSimian. J Field Robot. 2015;32(2):255–274.

Hong D. Biologically inspired locomotion strategies: novel ground mobile robots at RoMeLa. The 3rd International Conference on Ubiquitous Robots and Ambient Intelligence. 2006; Seoul, Korea. p. 15–17.

Kim S, Kim B. Dynamic ultrasonic hybrid localization system for indoor mobile robots. IEEE Transactions on Industrial Electronics. 2013;60(10):4562–4573.

Lakhmani S, Abich J 4th, Barber DJ, Chen J. A proposed approach for determining the influence of multimodal robot-of-human transparency information on human-agent teams. Proceedings of the 10th International Conference of Augmented Cognition. 2016; Toronto, Canada. p. 296–307.

Markoff J. Seeking robots to go where first responders can't. NYTimes.com. 2012 [accessed 2016 July 6]. http://www.nytimes.com/2012/04/10/science/pentagon-contest-to-develop-robots-to-work-in-disaster-areas.html?_r=0

Okamura A, Smaby NC. An overview of dexterous manipulation. Proceedings of the 2000 IEEE International Conference on Robotics and Automation, Symposium on Dexterous Manipulation; 2000; 1, p. 255–262.

Pointeau G, Petit M, Dominey P. Successive developmental levels of autobiographical memory for learning through social ineraction. IEEE Transactions on Autonomous Mental Development. 2014 Sep;6(3):200–212.

RobotWorx. FANUC Robotics. 2016 July 6 [accessed 2016 July 6]. www.robots.com: https://www.robots.com/fanuc

Russell L, Goubran R, Kwamena F. Personalization using sensors for preliminary human detection in an IoT environment. IEEE International Conference on Distributed Computing in Sensor Systems; 2015; Fortaleza, Italy; p. 236–241.

Seok S, Wang A, Chuah M, Otten D, Lang J, Kim S. Design principles for highly efficient quadrupeds and implementation on the MIT Cheetah robot. IEEE International Conference on Robotics and Automation (ICRA); 2013; Karlsruhe, Germany; p. 3307–3312.

Shill J, Collins EJ, Coyle E, Clark J. Tactile surface classification for limbed robots using a pressure sensitive robot skin. Bioin Biom. 2015;10(1).

Soffar H. The advantages and disadvantages of robots in the factories. 2015 Apr 14. [accessed 2016 July 6]. www.online-sciences.com: http://www.online-sciences.com/technology/the-advantages-and-disadvantages-of-robots-in-the-factories/.

Sutherland J, Baillergeon R, McKane T. Cordon and search operations: a deadly game of hide and seek. Air Land Sea Bulletin: Cordon and Search (2010–2013). 2010:4–10.

Wright C, Johnson A, Peck A, McCord ZN, Gianfortoni P, Gonzalez-Rivero M, Choset H. Design of a modular snake robot. Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems; 2007; San Diego, CA; p. 2609–2614.

Appendix A. Technical Exchange Meeting (TEM) Agenda

This appendix appears in its original form, without editorial change.

RCTA-Technical Exchange Meeting

December 8th & 9th (Tues - Wed)

Institute for Simulation and Training, Partnership III-Room 233

3039 Technology Parkway, Orlando, FL 32826

Program Agenda

Day 1 (Tues Dec 8th)

0800	0830	Meeting Registration	
		Orienting session	
		Presenter	**Topic**
0830	0840	Daniel Barber	Welcome, introductory remarks, and housekeeping
0840	0850	Randy Shumaker	IST & RCTA Overview
0850	0900	Florian Jentsch	RCTA - HRI Overview
0900	0910	Daniel Barber	The Purpose of the TEM
		Expectations of HRI with Unique Mobility Robots (UMR)	
0910	0920	Former SSG Thaddeus Taylor	Cordon and Search Presentation
0920	0940	DMUM Speaker - Jonathan Clark	Current and future state of UMR and the impact on HRI
0940	1025	Breakout sessions	Initiate small group discussion about what is expected of UMR functionality/capability. How should HRI support DMUM?
1025	1110	Group Discussion	As a whole, discuss group results
1110	1230	Luncheon Break	
1230	1250	Perception Speaker - Martial Hebert	Current and future state of Perception and the impact on HRI
1250	1335	Breakout sessions	Initiate small group discussion about what is expected of Perception functionality/capability. How should HRI & Perception support each other to achieve Soldier-UMR teaming?
1335	1420	Group Discussion	As a whole, discuss group results
Break (10 min)			
1430	1450	Intelligence Speaker - Stuart Young & Douglas Summers-Stay	Current and future state of Intelligence and the impact on HRI
1450	1535	Breakout sessions	Initiate small group discussion about what is expected of Intelligence functionality/ capability. How should HRI & Intelligence support each other to achieve Soldier-UMR teaming?
1535	1620	Group Discussion	As a whole, discuss group results
1620	1630	Daniel Barber	Closing remarks for the day and plans for Day 2

Day 2 (Wed Dec 9th)

		Panel Session – Program of Implementation(Road map for HRI)	
0830	0900	Morning welcome	Coffee provided

0900	0940	All thrust area speakers	Presentations recapping the discussion of the previous day for each thrust area
0940	1025	Group Discussion	Develop program of implementation
Break (10 min)			
1035	1120	Group Discussion	Recap; continue developing program of implementation
1120	1130	Daniel Barber	Closing remarks for the meeting
1130	1245	Luncheon Break	
1245	1500	IST Lab Tour	Research labs at IST

INTENTIONALLY LEFT BLANK.

Appendix B. List of Discussion Questions

This appendix appears in its original form, without editorial change.

Overall HRI with UMR Discussion Points:

- What are the social impacts of interacting with unique mobility robots?
    - Do various types of robot manipulations (e.g. hand reaching out, slithering on the ground, climbing a wall) effect shared mental models? Shared cognition? Trust?
    - What are the information requirements for computational models to support social interaction with unique mobility robots?
    - What types of behaviors must unique mobility robots display in order to communicate appropriate signals to convey a certain meaning?
- How interaction with unique mobility robots will impact Soldier's mental workload, preference for usability, and situation awareness?
- What level of transparency is needed to understand the robot's behavior in order to make appropriate informed decisions?
- How should the robot operators be trained and does the training need to be more extensive for robots that employ unique mobility and manipulation?

DMUM:

- What types of manipulation is a robot able to perform that is beyond human capabilities?
- Should robots exhibit more mechanical or biological motion? Does it matter?
    - How will a Soldier respond to the robots unique mobility and manipulation behavior? For example, should the robot move in a way that matches or leverages existing Soldier mental models?
- What type of unique mobility robots are we expecting (e.g. climbing, jumping, and sliding)?
- What functionality should we expect a unique mobility robot to have?
    - How should that functionality be initiated through the multimodal communication (MMC)?
    - What commands and data should the MMC support to interact with unique mobility robots?
    - Are there other types of devices that may be more suitable for interaction with unique mobility robots (e.g. HoloLens, Google glass)?
- Are there physical characteristics of UMR that we can use to convey information to Soldiers? For example, pointing using a manipulator or other instrument.

Perception:

- What can a robot perceive that is beyond human capabilities (e.g. thermal imaging)?
    - Which of those capabilities would benefit a Soldier to have access to?
- What features (e.g. terrain, objects, inclined topography) of 3D complex environments is perception able to classify that impacts unique mobility planning, navigation, and manipulation?
    - How do we convey this to a Soldier?

    - Are there opportunities for a Soldier to assist in the identification of these environmental features?

Intelligence:

- What parameters about complex 3D environments should/will a Soldier have available when issuing commands to a robot? For example, “Climb over the debris and go to the back of the building.” “Covertly screen the back of the building.”
    - What language/vocabulary (i.e. speech, gestures, and tactile sequences) will be needed to support these parameters?
- What level of the robot’s self-awareness within complex 3D environments can/should be represented for Soldiers? For example, conveyance of areas that would support covert navigation.
- Is there information a Soldier can provide to intelligence components to assist in successful completion of tasks? For example, a robot request may be, “Can I climb over this?”
- What tradeoffs exists when comparing different solutions to a requested command? For example, “Should I travel through a faster but less energy efficient route or a longer energy conservative route?”

INTENTIONALLY LEFT BLANK.

Appendix C. Workshop Participants

This workshop was by invitation only and drew participants from academia, industry, and government agencies. Table C-1 lists their names and affiliations.

Table C-1 RCTA TEM 2015 workshop participants and their affiliations

Last name	First name	Affiliation
Abich	Julian	University of Central Florida
Andrews	John	Office of Naval Research
Baran	David	US Army Research Laboratory
Barber	Daniel	University of Central Florida
Best	Andrew	University of Central Florida
Bornstein	Jon	US Army Research Laboratory
Chen	Jessie	US Army Research Laboratory
Clark	Jonathan	Florida State University
Collins	Emmanuel	Florida State University
Dean	Robert	General Dynamics Land Systems
DiBerardino	Chip	General Dynamics Land Systems
Flascher	Oded	Advanced Technology
Garcia	Andre	Northrop Grumman
Gupta	Nikhil	Florida State University
Guznov	Svyatoslav	US Air Force Research Laboratory
Hancock	Peter	University of Central Florida
Hebert	Martial	Carnegie Mellon University
Hill	Susan	US Army Research Laboratory
Hodnik	Debra	National Ground Intelligence Center
Hudson	Irwin	US Army Research Laboratory
Jentsch	Florian	University of Central Florida
Kapalo	Kate	University of Central Florida
Kasper	Karissa	University of Central Florida
Kessler	Theresa	University of Central Florida
Kopinsky	Ryan	Florida State University
Kwon	Heesung	US Army Research Laboratory
Lebiere	Christian	Carnegie Mellon University
MacArthur	Keith	University of Central Florida

Table C-1 RCTA TEM 2015 workshop participants and their affiliations (continued)

Last name	First name	Affiliation
Machado	Daniel	US Army Training and Doctrine Command's Capabilities Manager–Explosive Ordnance Disposal
Marge	Matthew	US Army Research Laboratory
Matthews	Gerry	University of Central Florida
Murphy	Karl	Robotic Research
Navarro-Serment	Luis	Carnegie Mellon University
Oh	Jean	Carnegie Mellon University
Padero	Charles	University of Central Florida
Phillips	Elizabeth	University of Central Florida
Prevost	Zachary	US Army Engineer Research and Development Center
Reinerman-Jones	Lauren	University of Central Florida
Summers-Stay	Douglas	US Army Research Laboratory
Tahmoush	David	US Army Research Laboratory
Talone	Andrew	University of Central Florida
Taylor	Thaddeus	QinetiQ North America
Teo	Grace	University of Central Florida
Young	Stuart	US Army Research Laboratory

List of Symbols, Abbreviations, and Acronyms

3-D	3-dimensional
C&S	cordon and search
CMU	Carnegie Mellon University
DMUM	dexterous manipulation and unique mobility
FSU	Florida State University
GDLS	General Dynamics Land Systems
HRI	human–robot interaction
IRA	Integrated Research Assessment
RCTA	Robotics Collaborative Technology Alliance
TEM	technical exchange meeting
UCF	University of Central Florida
UGV	unmanned ground vehicle
UMR	unique mobility robot

1 (PDF) DEFENSE TECHNICAL
INFORMATION CTR
DTIC OCA

2 (PDF) DIRECTOR
US ARMY RESEARCH LAB
RDRL CIO L
IMAL HRA MAIL & RECORDS
MGMT

1 (PDF) GOVT PRINTG OFC
A MALHOTRA

1 (PDF) ARMY RSCH LAB – HRED
RDRL HRB B
T DAVIS
BLDG 5400 RM C242
REDSTONE ARSENAL AL
35898-7290

1 (PDF) ARMY RSCH LAB – HRED
RDRL HRB A
R SPENCER
BLDG E2929
DESERT STORM DR
FORT BRAGG NC
28310-0001

8 (PDF) ARMY RSCH LAB – HRED
SFC PAUL RAY SMITH
CENTER
RDRL HRO COL H BUHL
RDRL HRF J CHEN
RDRL HRA I MARTINEZ
RDRL HRR R SOTTILARE
RDRL HRA C A RODRIGUEZ
RDRL HRA B G GOODWIN
RDRL HRA A C METEVIER
RDRL HRA D B PETTIT
12423 RESEARCH PARKWAY
ORLANDO FL 32826

1 (PDF) USA ARMY G1
DAPE HSI B KNAPP
300 ARMY PENTAGON
RM 2C489
WASHINGTON DC 20310-0300

1 (PDF) USAF 711 HPW
711 HPW/RH K GEISS
2698 G ST BLDG 190
WRIGHT PATTERSON AFB OH
45433-7604

1 (PDF) USN ONR
ONR CODE 341 J TANGNEY
875 N RANDOLPH STREET
BLDG 87
ARLINGTON VA 22203-1986

1 (PDF) USA NSRDEC
RDNS D TAMILIO
10 GENERAL GREENE AVE
NATICK MA 01760-2642

1 (PDF) OSD OUSD ATL
HPT&B B PETRO
4800 MARK CENTER DRIVE
SUITE 17E08
ALEXANDRIA VA 22350

ABERDEEN PROVING GROUND

11 (PDF) DIR USARL
RDRL HR
J LOCKETT
P FRANASZCZUK
K MCDOWELL
K OIE
RDRL HRB
D HEADLEY
RDRL HRB A
M LAFIANDRA
RDRL HRB C
J GRYNOVICKI
RDRL HRB D
C PAULILLO
RDRL HRF A
A DECOSTANZA
RDRL HRF B
A EVANS
RDRL HRF C
J GASTON
RDRL HRF D
A MARATHE

3 (PDF) UNIVERSITY OF CENTRAL
FLORIDA
J ABICH
D BARBER
F JENTSCH

2 (PDF) FLORIDA STATE UNIVERSITY
J CLARK
E COLLINS

INTENTIONALLY LEFT BLANK.